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Plastic Nets in Agriculture: A General Review of Types and Applications

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Abstract. *At the moment, there are a large number of agricultural net types on the market characterized by different structural features such as type of material, type and dimensions of threads, texture, mesh size, porosity / solidity and weight; by radiometric properties like color, transmissivity/reflectivity/shading factor; by physical properties like air permeability and several mechanical characteristics such as tensile stress, strength, elongation at break, and durability. Protection from hail, wind, snow, or strong rainfall in fruit-farming and ornamentals, shading nets for greenhouses and nets moderately modifying the microenvironment for a crop are the most common applications. A systematic review of the current state-of-the-art of structural parameters, standard and regulations, most common agricultural net applications, and their supporting structures has been developed by means of a literature study, technical investigations, concerning characteristics and use of nets. As a result, the survey highlighted that in many cases different, not even similar, net types were adopted for the same application and the same cultivations by various growers. Results show that neither growers nor net producers have clear ideas about the relationship between the net typology optimization for a specific application and the construction parameters of the net. The choice often depends on empirical or economic criteria and not on scientific considerations. Moreover, it appears that scientifically justified technical requirements for nets used in specific agricultural applications have not been established yet.*

Keywords. Permeable membrane, Plastic net, Covering systems.

Plastic nets are widely used in various agricultural applications: protection from hail, wind, snow, or strong rainfall in fruit-farming and ornamentals, shading nets for greenhouses and nets moderately modifying the microenvironment around a crop are the most common cases. Moreover, nets for the protection against virus-vector insects and birds, as well as for harvesting and post-harvesting practices are often used.

In the market, both woven and non-woven products are defined as nets. In order to avoid misunderstanding, the following definition of plastic nets is proposed: a plastic net is a product made of plastic threads connected together with each other, in a woven or knitted way forming a regular porous geometric structure and allowing fluids (gases and liquids) to go through .

The most widely used raw material for agricultural nets is high density polyethylene (HDPE). Polypropylene (PP) is also used as raw material for nets, mostly for the production of non-woven layers.

It is not possible to determine the European consumption of agricultural nets because no data are available from agricultural and manufacturers associations at a European level. Moreover, the net producers are not able to define the consumption of agricultural nets, because an amount of their production is actually sold for non-agricultural purposes, such as shading nets for car parking, permeable coverings of scaffoldings, construction of provisional fences, anti-insect nets for windows, fishing nets, etc. However, in Italy, the estimated consumption of HDPE for agriculture net production is 5.300 t per year, while the total consumption in agriculture of HDPE is 30.000 t per year and of PP is 46.500 t per year (Scarascia et al. , 2005).

For the European normative situation, no standard exists concerning agricultural nets. There are currently only a few national standards regarding agricultural nets and films specifically. Concerning nets, there is a set of Italian Standards that covers a wide range of agricultural net properties. Other national standards deal partly with agricultural films such as the French standard NF EN 13206 (NF, 2002) and the Italian standards UNI 9738 (UNI, 1990) and UNI 9298 (UNI, 1988).

A systematic review of the current agricultural applications of nets in Europe has been developed by means of a literature study, technical investigations, interviews with permeable covering producers and specialized greenhouse builders, as well as insurance organizations and growers, who are familiar with permeable cladding (net) applications.

Net Types

Net types are characterized by different structural features like type of material, type and dimensions of threads, texture, mesh size, porosity/solidity and weight; by radiometric properties like color, transmissivity/reflectivity/shading factor; by physical properties like air permeability and by several mechanical characteristics such as tensile stress, strength, elongation at break, and durability (Castellano and Russo, 2005). Normally the available dimensions of nets vary a lot in both width and length. Widths usually vary from 1 to 6 m or from 12 to 20 m (depending on the type of net) and lengths from 25 to 300 m. Wider nets are constructed by attaching the required number of nets in width. A first classification of nets can be based on type of material, type of threads and texture, color, and additives used.

Type of Material

For agricultural nets, primarily high density polyethylene (? $_{HDPE}$ = 940-960 kg/m ^{3}) is used: it is a non-toxic material, which can be used in direct contact with plants; it is completely recyclable; easily convertible; waterproof; durable, if stabilized to ultra violet (UV) radiation agents are added in the correct quantity; and has good mechanical characteristics (tensile strength s = 20 ÷ 37MPa, plastic strain e = ? L/L = 200 ÷ 600%).

Polypropylene (? PP = 900-910 kg/m ^{3}) is used as raw material in the production of non-woven layers. This kind of membrane is in horticulture and in orchards applied as direct cover on plants to protect cultivations from rain, frost, or wind. Non-woven layers are characterized by a very low structural resistance and cannot be used as coverings of structural frames.

Starch-based biodegradable materials are also used in some innovative agricultural net productions. At the end of their life, biodegradable materials can be disposed directly in soil or can be incorporated in a composting plant with organic materials, such as food and vegetable residues and manure, in order to generate carbon-rich compost (Narayan, 2001). Biodegradable materials are not very common in the market due to their high costs, compared with other plastic materials, and because of the reduction of their physical and mechanical properties when exposed for prolonged periods to climatic agents, mainly to solar radiation (Scarascia et al., 2004).

Type of Threads and Texture

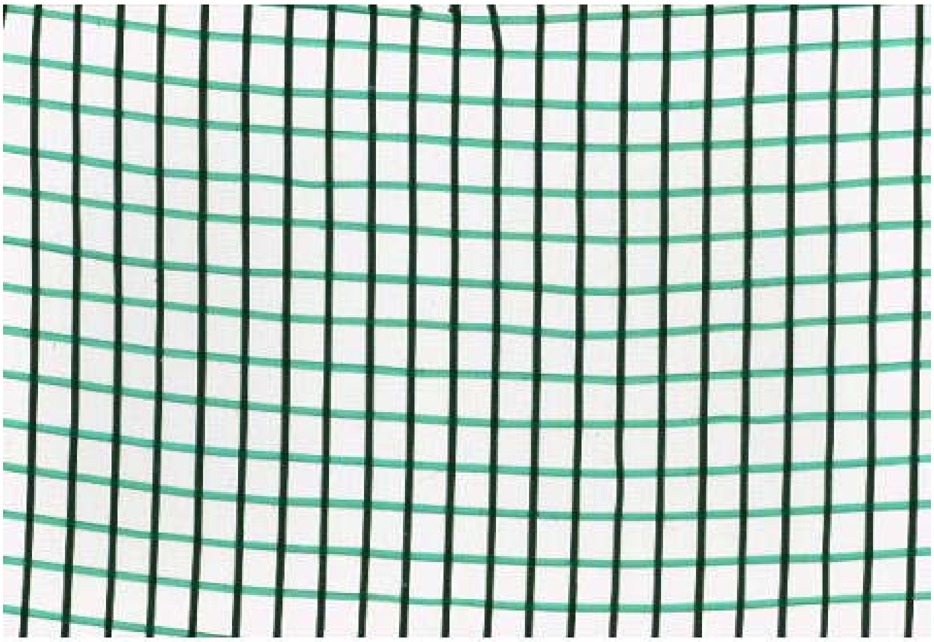
Threads of HDPE are produced in two main types: round monofilaments or flat tapes. Round monofilaments are extruded directly by the HDPE compound, but in order to obtain flat tapes it is first necessary to produce the film of wanted thickness and color and finally to cut it. Depending on the kind of texture three main typologies of nets can be defined for common agricultural applications: flat woven or Italian; English or Leno; knitted or Raschel (fig. 1).

Flat woven is characterized by a simple orthogonal weave between weft and warp threads. In the loom processing, weft is the horizontal thread which pass through the vertical threads -- the warp -- forming the fabric. Flat woven nets are light and stable in their shape, but they are relatively stiff and they resist deformations (fig. 1a).

English woven is a modified flat woven net and it is produced with the same type of looms. It is based, like the flat woven one, on the orthogonal weave between weft and warp threads but with a double thread in weft direction, enclosing the warp thread in between (fig. 1b). English woven nets are used when a more rigid protective covering is required, like for vineyards during strong hail storms.

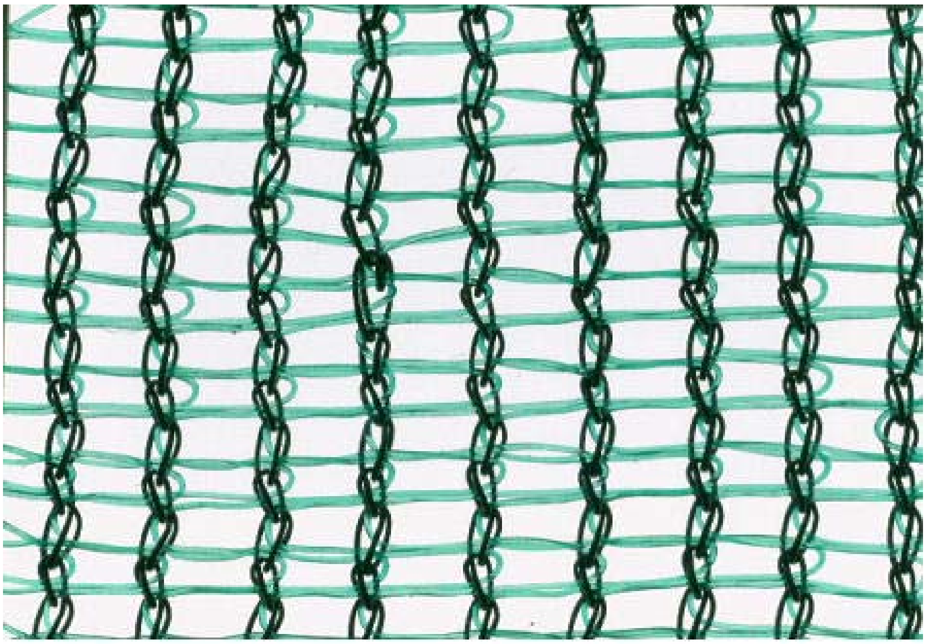
Raschel looms produce nets with longitudinal 'chains' and transversal knitted threads (fig. 1c). In Raschel nets all threads are linked with each other in order to prevent the unraveling of threads, for example as a result of strong wind or hail storms.

Selvages on the borders usually stabilize and secure the net and reinforced buttonholes enable nets to be installed more easily and quickly to the supporting structure.



(a)

(b)



(c)

Figure 1. (a) Scheme of monowire flat woven or Italian texture; (b) monowire and tape English woven or Leno texture; (c) monowire knitted or Raschel texture. In the figure the warp thread of the loom is vertical; the weft thread of the loom is horizontal.

Mesh Size, Porosity, Solidity, and Weight

Depending on the texture, the single threads are connected to each other in such a way that they form a regular porous geometric structure, the mesh. The mesh size is the distance between two threads in warp or weft direction. The mesh size is given in mm for both the warp threads and weft threads and varies from 0.2 to 3.1 mm for insect nets, from 1.7 to 7.0 mm for shade nets, from 2.5 to 4.0 mm for anti-hail nets, from 1.8 to 7.0 mm for windbreak nets, while higher values, 3 to 4 cm, characterize the anti-birds nets.

The porosity of a porous geometric structure represents the percentage of open area of the net divided by the total area of the net. It can be evaluated by means of three methods: radiation balance, interception of solar radiation, and analysis of images of materials (Cohen and Fuchs, 1999). Solidity is the opposite of porosity and represents the percentage of solid area of the nets divided by the total area of the net. Solidity is a parameter used in the evaluation of the wind force on porous geometric structures in accordance to structural Eurocode ENV1991-2-4 (ENV, 1997).

The thickness of a net is given by the thickness of single threads in millimeters (mm). Generally it varies from 0.25 mm up to 0.32 mm. The weight of plastic nets depends on the thickness of threads, the texture, and on the mesh size: generally, it varies from 15 g/m ^{2} up to 325 g/m ^{2}. The only Standard related to the definition of the weight of the nets is provided by Italian Bureau of Normalization: UNI 9401/89- (UNI, 1989a) Reti in plastica per l'agricoltura- Determinazione della massa per unità di superficie (Agricultural plastic nets - definition of mass per square unit). Until the introduction of the metric system, the unit of the mechanical quality of silk and man-made threads (still used in the United States and in many other countries) was the denier (den). It represents the weight of a 900 m length thread, where the weight of a standard den is 100 g: 1 den = 0.11 g/m. The denier can be considered as an indication of the area of the cross section of a thread and consequently can be associated to its mechanical resistance. Other units used in the market are: grex = 10 $^{-7}$ kg/m and tex = 10 $^{-6}$ kg/m.

Mechanical Properties

Additives are used in order to improve or change the mechanical and physical characteristics of the plastic net and its durability (aging behavior). Additives are also used in order to increase the permeability to the water, for fire retardance of the polymer, and to reduce the accumulation of dust (antistatic additives). They are produced in grains and mixed with HDPE, with appropriate proportions in order to form the compound. The most common ones are chromatic and UV stabilizers.

The stability of the mechanical properties of HDPE mainly depends on its resistance to UV radiation, which is the main cause of HDPE degradation (Doble and Kumar, 2005). The UV degradation resistance of the net is expressed as the amount of kilolangley (kly) necessary to reduce the tensile strength of the net to 50% of the original value (Note: the unit of kilolangley expresses the global incident solar irradiation: 1 kly = 1 k cal/cm ^{2} = 41.84 MJ/m ^{2}).

UV stabilizers increase the resistance to commercial nets against solar radiation up to 400-800 kly, which corresponds to a durability of the polymer of 5 to 6 years in mild climates such as the Mediterranean climate (100-120 kly/yr) or 3 to 4 years in tropical areas (140-160 kly/yr). The evaluation of the stability of the polymer against UV radiation is described in the following standards: ASTM D4329/99 (ASTM, 1999) - Standard practice for fluorescent UV exposure of plastics; ASTM G154/00 (ASTM, 2000b) - Standard practice for operating fluorescent light apparatus for UV exposure of non-metallic materials; ASTM G151/00 (ASTM, 2000a) - Practice for exposing non-metallic materials in accelerated test devices that use laboratory light sources; UNI ISO 4892-1/2/3 (UNI-ISO, 2002) - Materie plastiche - Metodi di esposizione a sorgenti di luce di laboratorio [Plastic materials- exposing to laboratory light sources methods].

The durability of the net also depends on the kind of contact with structural elements, such as columns and cables, on the environmental temperatures (HDPE is a thermoplastic material), on the use of chemical pesticides containing sulphur and/or chlorine, and even on the chemical composition of the objects placed in contact with the material (for example metal posts) which can generate a premature chemical deterioration of the product (hot spots) (Dilara and Briassoulis, 2000). A premature degradation can also be caused by mechanical stress due to unusual climatic environmental conditions in the area such as wind and hail storms.

Table 1. Physical and mechanical characteristics of most common agricultural nets.

Agricultural Application	Thread [a]	Shading (%)	UV Res. (kly)	Areic Mass (g/m ^{2})	Br Warp [b] (kN/m)	Br Weft (kN/m)	Plastic Strain (%)	Den
Shading	R, T	25-90	400-800	50-250	4-10	2-15	20-30	450-800
Anti-hail	R, T	10-25	400-800	30-70	4-7	2-4	20-40	500-700
Anti-insects	R	10-20	400-600	70-130	4-5	2-4	20-30	300-450
Windbreak	R, T	30-70	400-800	60-180	5-15	4-18	20-35	300-450
Anti-birds	R	5-15	300-600	10-30	0.5-2.5	0.5-2.5	20-30	300-450

[a] Round (R); Tape (T) (Castellano and Russo, 2005).

[b] "Br" in warp and weft direction is the ratio between the breaking load and the length of the net sample according to UNI9405 (UNI, 1989e).

Only a few norms exist to characterize other mechanical properties of agricultural nets. The most important mechanical characteristics of nets are the plastic strain and the tensile strength in warp and weft direction (table 1). They are defined by Italian Standard UNI 9405 (UNI, 1989e) - Reti in plastica per l'agricoltura- Determinazione della forza e dell'allungamento a rottura [Agricultural plastic nets- evaluation of tensile strength and plastic strain]. Some manufacturers indicate the tensile strength as the ratio between the breaking load and the area of the cross section of the sample in N/mm^2, or the breaking load and the length of the net sample in N/m or in units of the deniers in N/den. The stress-strain test highlights that the tensile strength of the single thread and of the total net are completely different (Briassoulis et al., 2007a, 2007b). The areic mass (g/m^2) is defined by the Italian Standard UNI 9401 (UNI, 1989a). Reti in plastica per l'agricoltura- Determinazione della massa per unità di superficie [Nets for agricultural uses- determination of the mass per unit area] (table1).

Color

The color of the net is obtained by mixing chromatic additives to HDPE grains before the production of the compound. The most common net colors are: black, green, or transparent. Transparent nets are used for those applications in which the shading effect of the net is considered as a negative consequence of net performances. Black nets are generally used for shading installations in which the reduction of incoming solar radiation is desirable (fig. 2). The black color is obtained by using 'carbon black' additive, which also acts as a UV-stabilizer and consequently the durability of nets with black threads is higher than transparent threads. Carbon black is usually added in a quantity of less than 1%, since higher quantities could decrease the mechanical stability of the thread. Other colors are obtained by means of pigments: for example, phthalocyanine-based additives are used to obtain blue and green nets. Colored nets are developed to modify the spectral transmittance of the solar radiation (fig. 3) in order to obtain different light-induced effects on the plants, such as the increasing of the fruit size and controlling the duration of the production period (Shahak et al., 2002). Red and yellow nets can stimulate the growth, blue nets can cause dwarfism in ornamental plants, whilst grey nets stimulate branching and produce 'bushy' plants with short branches and small leaves. Modifications of the flowering period and of the quality of the production were observed in cut flowers species covered with colored nets (Oren-Shamir et al., 2001; Priel, 2001; Shahak et al., 2002). Silver nets are produced by extruding an HDPE tape thread together with an aluminum layer and provide high reflectance. Silver nets are used both inside the greenhouses as thermal screen and outside, as a shading membrane.

Limited data are available on the application of colored nets on vegetable crops (Bar Tsur et al., 1985; Baille, 1989; La Malfa, 1993; Leonardi et al., 2004). However, a higher air temperature inside the screen house (1.5-3.0 ° C) was observed when a red net was used, compared to a transparent net. Colored nets are also used for insect-proof applications because they may attract some insects (Bell and Baker, 1997). More research is needed to quantify the effects of net color on inside greenhouse climate and crop response.

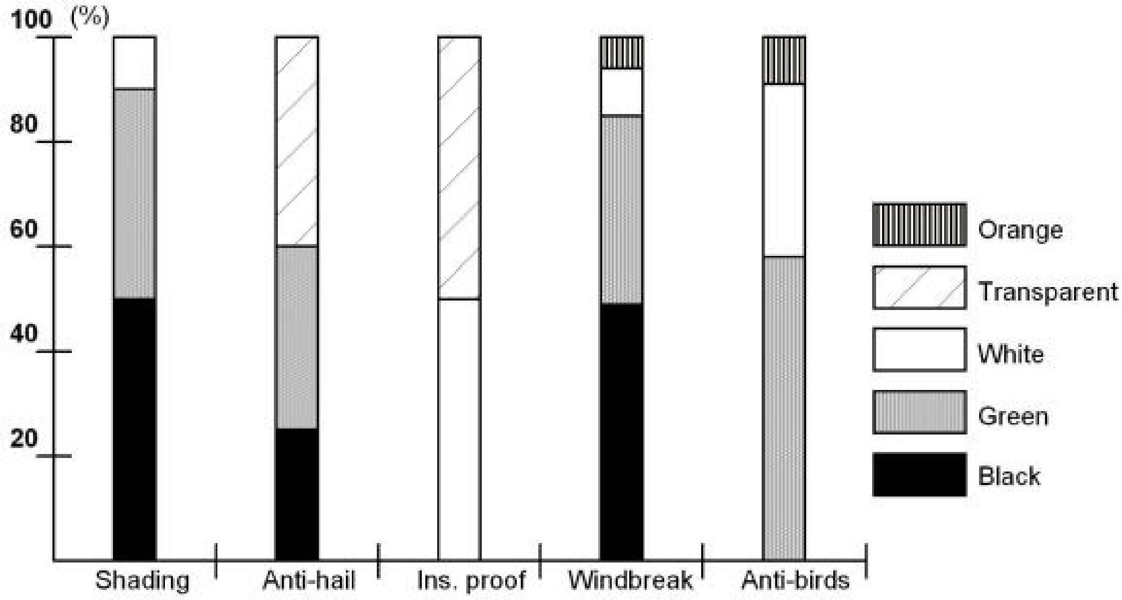


Figure 2. Colors of nets depending on their agricultural application in Italy (Castellano and Russo, 2005).

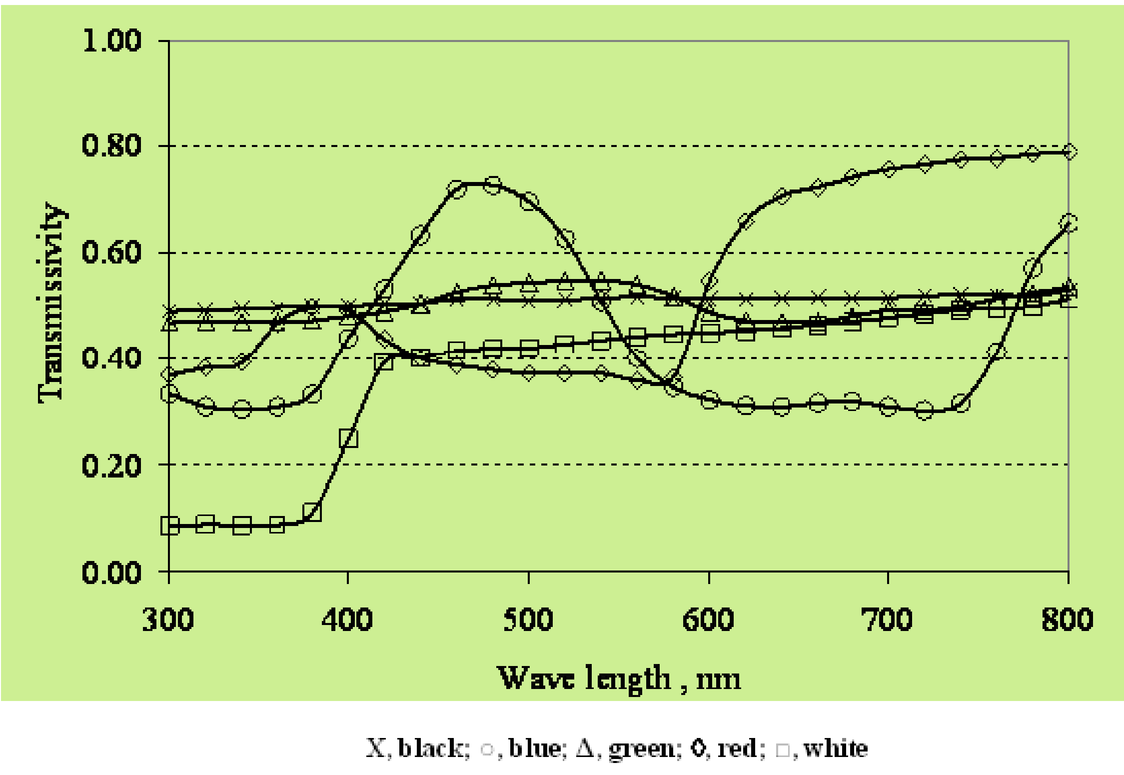


Figure 3. Diagram of transmissivity measured in 300- to 800-nm wave length range on different colored nets tested in laboratory.

Transmissivity, Reflectivity, and Shading Factor

The radiometric properties of agricultural nets, such as transmissivity, reflectivity, shading factor, or the capability to modify the quality of the radiation passing through the net influence the quality of the agricultural production and the aesthetic characteristics of the netting system. During the last decade research was carried out on colored nets to determine the influence on the morphology of plants (Oren-Shamir et al., 2001; Shahak and Gussakovsky, 2004; Shahak et al., 2004; Elad et al., 2007; Shahak et al., 2007) and on the effect of UV-blocking nets on insect behavior (e.g. Antignus et al., 1998; Kumar and Poehling, 2006), however, a characterisation of different types of nets for different purposes is still lacking. All construction parameters of the net, combined with the shape of the structure, the position of the sun and the sky conditions affect the radiometric performance of the permeable structure (Castellano and Russo, 2005; Castellano et al., 2006; Hemming et al., 2008). Nets are non-uniform materials, for this reason, radiometric properties should be studied on large enough samples to avoid any small-size effects.

Photosynthetically Active Radiation (PAR, 400-700 nm) transmittance is the most important radiometric property of covering materials from the agronomic point of view, since PAR is necessary for plant photosynthesis and growth. In the PAR region, the transmission of perpendicular light and light under different angles of incidence with reference to the net surface is important to characterize the material behavior on clear days, whereas the transmission for diffuse light characterises the material behavior on cloudy days. The radiation range from 300 to 800nm is important for plant growth, mostly for morphogenetic responses. This radiation is therefore called Morphogenetically Active Radiation (MAR) by some authors (e.g. Varlet-Grancher and Gautier, 1995). The total solar transmission (300-2500 nm) of materials is important to quantify the amount of energy entering the net structure, which has an important influence on the microclimate inside the screen house. Whereas in non-permeable structures (e.g. plastic film greenhouses) the transmission for heat radiation (>2.5 μ m) is considered to play a major role, it will be less important for open net structures, where convective heat exchanges are more important than radiative heat exchanges. The haze is the percentage of the transmitted direct radiation scattered by a material. Materials with a high haze create an indoor environment with diffuse light, which is preferable for many crops (Hemming et al., 2005, 2007), particularly in Southern European countries. Transparent or semitransparent threads may be used for reducing excessive solar radiation and generate mild and more uniform internal light conditions. The color of the material and the light reflection especially of the wavelengths visible to the human eye (VIS, 380-760nm) are interesting criteria to determine the aesthetic value of the net structure and the environmental impact.

The radiometric behavior of a net covered structure strongly depends on the external light conditions. The transmittance of the covering system also varies with the angle of incidence of the solar radiation in the case of a clear sky. For example, a large angle of incidence combined with a clear sky may create a strong shading effect during daytime, while an overcast sky results in a smaller loss of incoming radiation. The direct light transmittance as a function of the angle of incidence is also an important radiometric property for nets, which is dependent on the three-dimensional structure of the material. The light transmittance with respect to a diffuse light source is also investigated since it provides information about the performance of the net under an overcast sky. These properties describe the seasonal and diurnal performance of the material.

A very common commercial parameter defining a net is the shading factor which describes the ability of a net to absorb or reflect a certain part of sun radiation (fig. 3). It depends on the color, mesh size, and texture of the net (table 2). It is defined by Italian Standard UNI 10335/94 (1994a) - Reti in plastica per l'agricoltura- Determinazione del potere ombreggiante delle reti in fibra polietilenica [Agricultural plastic nets - evaluation of shading factor in polyethylene thread made nets] (table 1). Samples, 50- × 50-cm size, are put in a black box at a distance of 98 cm from the lighting source -- a 150-W incandescent lamp powered with stabilized voltage -- and at a distance of 2 cm from the luxmeter cell. The shading factor is defined as the ratio between luxmeter measurements with and without the net sample. In the future it has to be investigated which method is the best to characterize the light conditions in a net-covered structure at crop level in order to create optimum light conditions for crop growth and production. It may be necessary to work out tests and norms and new numeric models to help manufacturers and farmers to choose the optimum net for a defined net application.

Air Permeability

The air permeability is the ability of the net to transmit the air through it. It depends on many parameters such as air viscosity and speed, dimension and shape of threads, spaces between threads and the texture. U ndamaged porous screens usually used as thermal screens have permeability close to 10^{-11} m^2 and insect screens have, usually, permeability less than 10^{-8} m^2. (Miguel et al., 1997). The permeability and the porosity are basic parameters which influence both the pressure coefficients on the net and the climate under the nets, in terms of air speed, humidity, and temperature. While the air flow resistance of different kinds of insect nets is widely investigated (Miguel et al., 1997; Bailey, 2003; Valera, 2005; Harmanto et al., 2006), the air permeability of shading nets or anti-hail nets is unknown and is being studied by the authors in a current research project.

Agricultural Applications of Nets

The main agricultural applications of nets and net covered structures are: protection against meteorological hazards, insects, and little animals; reduction of solar radiation; and soil covering. Nets are also used for harvesting fruits such as olives, chestnuts, almonds, walnuts, and other little fruits; for packaging; and for post-harvesting operations such as collecting cut flowers and drying fruits. Nets installed in the vents of greenhouses or directly on trees are used to protect crops from insects, birds, and small animals such as rabbits, hares, and mice. Permeable coverings are used as soil covering in a wide range of application: for protected cultivation and garden centers in order to create walking areas; for soil mulching against weeds and as a barrier for roots; underneath wooden plank bridges, terraces, and ramps; and in fruit tree cultivations. The following information is based on information of several net producers, greenhouse manufacturers, and farmers in Europe.

It is not always possible to associate a net to a specific application, as in many cases they accomplish more functions at the same time, for example shading nets also protect crops from hail.

Protection Against Meteorological Hazards

One of the most important agricultural uses of plastic permeable coverings is to protect cultivations from wind, hail, snow, frost, and rain. Windbreak nets are used in order to: avoid mechanical damages (e.g. breaking of branches, flowers) and biological consequences (high evapo-transpiration, difficulties in pollination) due to the action of wind on crops; increase the quality of products by protecting them from dust, salt, and sand; reduce the wind load on agricultural structures; minimize the heat loss of animals due to ventilation in open livestock farms. Windbreak nets are usually fixed to a supporting structure consisting of columns or trusses, made of steel, concrete or wood, fixed at a foundation (fig. 4). Sometimes growers directly install them on trees planted at field borders. The wind reduction depends on the height of the structure, the porosity of the net and the distance of the fence from the cultivation (Richardson 1986; Richardson and Richards, 1995). The design of windbreak structures must find a balance between wind reduction effect and the structural costs, both depending on the net porosity. Moreover, low values of porosity have been found to induce wind vortices on the leeward side which are potentially dangerous for cultivations (Richardson, 1987). Windbreak supporting structures require a certain distance from the cultivation or from the agricultural building, which they have to protect, in order to avoid shading and subsequent reduced the crop production.

Figure 4. Windbreak net supported by a concrete structure in southern Italy.

Anti-hail nets prevent cultivation damages due to hail. They are largely used in open field applications, especially in fruit tree cultivations such as grape, peaches, apricots, and cherries, where they are installed with a specific supporting structure or directly applied on the cultivations. Anti-hail nets are considered, in some cases, a necessary protection of greenhouses covered with glass panels, where damages caused by hail could have onerous economical consequences on materials and crops and could be a danger for the safety of personnel working inside the greenhouse. In these applications, anti-hail nets also provide a reduction of incoming sun radiation during summertime. This can be considered a positive effect, especially in regions such as Southern Italy, where the most dangerous period for hail falls is in May-June and August-September. During these periods a reduction of solar radiation is required in order to reduce the temperature increase inside the greenhouse. Anti-hail nets on greenhouses require a specific supporting steel system connected to the greenhouse structure. The net can be moved along the supporting structure in order to control its shading effect as a function of the season and of meteorological conditions (fig. 5).

In open-field cultivations, like grapes, a pergola cultivation system is used. In a pergola cultivation system nets are applied on a supporting tensile structure with longitudinal and transversal steel cables tensioned to a supporting structure or to the ground with columns made of steel, concrete, or wood. In a pergola with traditional (hut) system (figs. 6 and 7) upper longitudinal wires are placed on the top of the columns at 4.0 to 5.0 m from the ground and lower transversal wires are installed at 2.5 to 3.0 m from the ground. The net is tensioned and fixed on both wires, from the ridge on longitudinal wires, and has a slope of 50% to 60% in order to allow the hail to fall off. The traditional system has been used in Europe for almost 20 to 30 years and it is appropriate for high trees with the same distance in longitudinal and transversal direction. In a flat net system, suitable for trees of 3.0- to 3.5-m height, both longitudinal and transversal wires are fixed on the top of the columns. The net is spread on and fixed to longitudinal wires. In this case the cables and the structure should be designed to resist hail and snow loads. Sometimes the net is fixed to the cables by means of 'break control' plaques, which break when the hail load exceeds a defined threshold, consequently the net falls preserving the structure. The flat net system is less expensive and easier to install than the pergola one. Sometimes, in flat net systems, the net is fixed to the top of columns by means of rubber bands, so that the net comes back in its position after the deformation due to the hail fall.

This system is also known as the French system. It is very important to avoid loads due to hail accumulation on the structure, which could induce the system to collapse if not designed properly. Those kinds of structures are empirically designed due to lack of data regarding climatic loads on nets and to the difficulties in calculation of tensile structures.

An anti-frost effect is usually reached by means of non-woven sheets spread on the cultivation, while in other cases it is considered a secondary effect of a net applied for other purposes.

Anti-rain nets avoid damages caused by heavy rain falls in orchards such as cherries; its effect is usually combined with anti-hail protection.

Figure 5. Shading and anti-hail system running over the roof of a glass greenhouse in southern Italy.

Figure 6. Orchard anti-hail netting on concrete structure in northern Italy.

Figure 7. Vineyard anti-hail netting on wooden supports in southern Italy.

Reduction of Solar Radiation

Shading nets are intended to reduce solar radiation in order to decrease air temperature inside greenhouses or to decrease the light level for several shade-loving crops like some ornamental plants. The efficiency of shading systems depends on the shading factor of the net. They are also used to prolong or to delay the harvesting period in sunny areas: for example, shading nets are used in southern Italy for 'cherry' tomato harvesting in August while, normally, they are harvested in June. Shading nets are used in screen houses for virus-free productions. However, the increase in air humidity and the reduction in air flow limits their use. Thermal screens are used inside the greenhouses in order to limit both convection and thermal radiative heat losses, especially during cold winter nights. Usually this kind of application requires aluminum color nets to increase the reflection of heat radiation emitted from inside the greenhouse.

Shading nets are usually supported by structures made of steel elements specially designed for greenhouses. These structures are generally designed with an arched (fig. 8) or a flat roof (fig. 9). Such supporting frames are empirically designed due to the lack of data regarding climatic loads on permeable coverings. When the net is used to shade greenhouses it can be deployed on a steel frame, supported by the main structure, with a distance from the covering of the greenhouse of almost 50 cm (fig. 10).

Thermal screens are installed inside the greenhouses, running on rails, generally at the gutter level (fig. 11).

Figure 8. Steel made vaulted roof with eaves shading structure in central Italy.

Figure 9. Steel made flat roof shading structure in central Italy.

Figure 10. Thermal and shading screens inside a greenhouse in northern Europe.

Protection Against Insects

Insect-proof nets are considered as an environmental and human health friendly alternative to pesticides and are usually employed in organic farming. Insect proof nets are used in screen house coverings, with simple or double layer, for virus-free productions. Screening to exclude insects can enhance integrated control programs, reducing dependence on chemical pesticides (Teerling et al., 1999; Hanafi, 2003). Moreover, screening may avoid inoculative feeding of the disease vectors, such as aleyrodidae, thrips, and aphids (Berlinger et al., 2002). Insect-proof nets are also used to avoid the escape of pollination insects, like bumble bees, from the greenhouse. For this kind of net the size of the mesh and the color, which may attract or repel insects, are the most important factors. Consequently, insect-proof nets are characterized by very low porosity and permeability. In order to limit the reduction of solar radiation transmittance white or transparent fibers are used. However, the reduction of air flow and the increase in relative humidity remain as negative effects.

Insect-proof nets are used as covering of specific supporting structure in the case of screen houses (figs. 11 and 12) or at greenhouses vents. The structures of screen houses are made of steel elements usually designed for greenhouses with arched, vaulted, or flat roofs. This kind of frame is empirically designed due to the lack of data regarding climatic loads on permeable coverings. When the insect-proof nets are used for greenhouse cultivations, they are installed at the vents in order to avoid the incoming of virus vector insects that can affect the crops. For some applications, such as the protection of apple trees from bugs, netting is laid on the soil and vertically on the border of the cultivation.

Figure 11. Impollination net system in Wageningen (Nl).

Figure 12. Screen houses for certified crop production with a double layer of anti-insect nets on the arches and with a stand-alone structure for the shading system at the University of Bari (It).

Other Applications

Nets installed on the vents of greenhouses or directly on the trees are used to protect cultivations from the attack of birds and small animals such as rabbits, hares, and mice.

Permeable coverings are used as soil covering in a wide range of applications: for protected cultivation and garden centers in order to create walking areas; for soil mulching against weeds; and as a barrier for roots, underneath wooden plank bridges, terraces, and ramps and in fruit tree cultivations.

Conclusions

The use of plastic nets is rapidly increasing in various agricultural applications. Protection from hail, wind, snow, or strong rainfall in fruit farming and ornamentals, shading nets for greenhouses, or nets for moderately modifying the microenvironment are the most common applications. At the moment, a large number of net types are characterized by different kinds of construction and performance properties, such as: type and dimensions of threads, texture, mesh size, solidity/porosity, weight, colors, shading factor, transmissivity/reflectivity, air permeability, durability, tensile strength, and elongation at break. A systematic review of the current state-of-the-art of most common agricultural applications of nets in Europe has been developed by means of literature study, technical investigations, interviews with permeable covering producers and specialized greenhouse builders and growers, who are familiar with structures with permeable nets. It appears that scientifically justified technical requirements for nets used in specific agricultural applications have not been established yet. During technical inspections it was noticed that in many cases different, not even similar, net typologies were adopted for the same application and the same cultivations by various growers. It is evident that neither growers nor manufacturers have clear ideas about the relationship between the net typology optimization for a specific function and the choice of the net, but this depends often on empirical or economic criteria and not on scientific considerations.

In a large number of agricultural applications, the radiometric characteristics of the net are the most important parameter, which have to be taken into account by the growers. If the transmissivity could be considered one of the main parameters involved in the choice of agronomic requirements of the netting system, the reflectivity of the net is strictly involved in the aesthetic assessment of the net-house in the rural landscape. In this case, nets with lower values of reflectivity should be chosen in order to reduce the visual impact of the building. Nets with an expected shading factor should have a high transmission for diffuse light. Insect nets and anti-hail nets should have as high as possible light transmission. The color of a net influences the spectral distribution of the radiation passing through the net absorbing their complementary colors, consequently the choice of the color of the net combined with the radiation requirements of the plant could be strategic to optimize the production and, more generally, the performance required. More research is needed to quantify the radiometric properties of nets and develop models to predict the light intensity and quality on crop level.

For other applications the air permeability and the air flow through the net are very important. Several quantitative data can be found for insect nets. However, quantitative data about other net types is lacking. Future research is needed here. The air permeability through other net types should be quantified by means of experimental data and modelling.

International testing standards have to be developed for the quantification of radiometric properties, air permeability, and mechanical characterisation of agricultural nets. In general a further development of agricultural nets is essential. The combination of threads with different properties and textures gives manufacturers the chance to manufacture nets for specific agricultural applications. Moreover, the effect of nets on crops has to be further investigated.

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